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Research Article

Modelling the present and future distribution of *Ambystoma altamirani* in the Transmexican Volcanic Belt, Mexico

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Abstract

Ambystoma altamirani is a critically endangered, microendemic amphibian species inhabiting the high-altitude rivers and streams of the Trans-Mexican Volcanic Belt (TMVB), a region experiencing severe ecological disturbances. This study aims to assess the current and future distribution of *A. altamirani* under different climate and land-use change scenarios using ecological niche modelling (ENM). We also evaluate the connectivity of suitable habitats and the overlap with existing natural protected areas (NPAs). Using occurrence records and environmental variables, we modelled the species' potential distribution under two climate models (CN85 and MP85) for 2050. The results indicate a significant reduction in suitable habitat, particularly in areas such as the Sierra de las Cruces and the Chichinautzin Biological Corridor, with habitat losses projected to reach up to 13.95% by 2050 under the CN85 scenario. Forest cover loss between 2001 and 2023 further exacerbates this threat, especially in municipalities like Tlalpan and Ocuilan. Our analysis highlights the urgent need for targeted conservation efforts, including the preservation of mixed *Abies-Pinus* forests and the restoration of degraded ecosystems. The findings underscore the critical importance of integrated conservation strategies that address habitat degradation, climate resilience and ecological connectivity to ensure the long-term survival of *A. altamirani*.

Key words: Axolotls, Central Mexico, climate change, conservation strategies, Ecological niche modelling, habitat fragmentation, mole salamanders

Introduction

Ambystoma altamirani is a critically endangered, microendemic amphibian species native to the high-altitude rivers and streams of the Transmexican Volcanic Belt (TMVB). This region, renowned for its rich biodiversity and high levels of endemism (Mastretta-Yanes et al. 2015; Sunny et al. 2017; Lemos-Espinal and Smith 2024) is one of Mexico's most ecologically disturbed areas, where habitat

degradation, invasive species and climate change are placing immense pressure on local ecosystems (García 2011; Parra-Olea et al. 2012; Figueroa et al. 2016). *Ambystoma altamirani* relies on the pristine conditions of oxygen-rich rivers and the integrity of temperate forests, particularly those dominated by *Abies* and *Pinus* species (Lemos-Espinal et al. 1999; Sunny et al. 2014; Lemos-Espinal et al. 2016; Woolrich-Piña et al. 2017). However, extensive land-use changes, including deforestation for agriculture, urban sprawl and both legal and illegal logging, have severely fragmented its habitat, further endangering the species (Lemos-Espinal and Smith 2015; Heredia-Bobadilla et al. 2017).

The TMVB, like many global biodiversity hotspots, is increasingly impacted by human activities that are driving significant biodiversity loss (CONABIO 2018). The Nevado de Toluca and Sierra de las Cruces, along with their protected natural areas, are amongst the key habitats where studies on *A. altamirani* have been conducted (Lemos-Espinal et al 2016; Heredia-Bobadilla et al. 2017; Camacho et al. 2020; Guerrero-de la Paz et al. 2020; Ruiz-Reyes et al. 2024). These critical areas have experienced substantial forest loss, particularly of *Abies* and *Pinus* forest, due to legal and illegal logging as well as land conversion. Between 2011 and 2014, significant portions of the Bosque de Agua were cleared and this deforestation trend has worsened in recent years, exacerbated by increased illegal logging during the COVID-19 pandemic (López-García and Navarro-Cerrillo 2021). In the Nevado de Toluca, clear-cut deforestation occurred in 49.6 hectares in 2018 alone (González-Fernández et al. 2022). Given that 91.1% of Mexico's *Abies* forests are located within the TMVB (Sunny et al. 2017), their conservation is vital, not only for biodiversity, but also for maintaining essential ecosystem services such as water regulation, which benefits over 25 million people in central Mexico (Sunny et al. 2017). The limited dispersal ability of *A. altamirani*, combined with habitat fragmentation, makes the species especially vulnerable to environmental changes (Ruiz-Reyes et al. 2024). Ruiz-Reyes et al. (2024) showed that the species' potential distribution is concentrated in areas where *Abies* forests are interspersed with *Pinus* forests, while areas dominated solely by *Pinus* are less suitable. This emphasises the need to preserve mixed forest habitats to support viable populations of *A. altamirani*. In addition to habitat loss, *A. altamirani* faces significant threats from invasive species, particularly *Oncorhynchus mykiss* (rainbow trout), which has been introduced into many high-altitude rivers in Mexico (Zambrano et al. 2010; Estrella-Zamora et al. 2018; Guerrero-de La Paz et al. 2020).

The TMVB is one of Mexico's primary agricultural regions and the expansion of crops like corn, potatoes and oats has led to the conversion of forested land into farmland (Galicia and García-Romero 2007; Caro-Borrero et al. 2024). Traditional farming practices often result in soil erosion and habitat degradation (Galicia and García-Romero 2007; Aryal et al. 2018; Caro-Borrero et al. 2024), while the widespread use of agrochemicals contaminates the rivers and lakes where *A. altamirani* lives (Caro-Borrero et al. 2024). This reduces habitat quality and increases the species' susceptibility to diseases and environmental stressors (Valbuena et al. 2021). Pollution from agricultural runoff affects the health of amphibian populations and reduces their resilience to environmental changes, further heightening the risk of extinction (Egea-Serrano et al. 2012). Predictions suggest that 25% of global biodiversity could be lost within the next 50 years due to such unsustainable practices (Lanz et al. 2018).

While habitat destruction and invasive species are pressing concerns, climate change presents a long-term challenge to the survival of salamanders and therefore *A. altamirani* (Parra-Olea et al. 2012; Vargas-Jaimes et al. 2021). As climatic conditions shift, habitat suitability for the species may decline in currently occupied areas, potentially limiting *A. altamirani* to smaller, more isolated populations (Sunny et al. 2014). Therefore, we hypothesise that *A. altamirani*'s future distribution will be significantly reduced due to the combined effects of habitat degradation and climate change and that current natural protected areas (NPAs) may not sufficiently encompass suitable habitats for the species under future climate scenarios (Ochoa-Ochoa et al. 2012).The primary objective of this study is to model the current and future distribution of *A. altamirani* under different climate and land-use change scenarios using ecological niche modelling. Additionally, we aim to evaluate the connectivity of suitable habitats for *A. altamirani* using functional connectivity analysis, assess the overlap between highly suitable areas and existing NPAs and determine whether current conservation efforts are sufficient to protect the species. By identifying critical habitats and regions most vulnerable to environmental change, we seek to provide actionable insights for improving conservation strategies and ensuring the long-term survival of *A. altamirani*.

Materials and methods

Species occurrence and environmental variables

A total of 198 occurrence records for *Ambystoma altamirani*, including geographical coordinates, were collected from both fieldwork and several online databases, such as REMIB (http://www.conabio.gob.mx/remib), UNIBIO (http://unibio.unam.mx/), the Global Biodiversity Information Facility (GBIF; https://www.gbif.org), HERPNET (http://www.herpnet.net/), the Vertebrate Network (VerNet, http://vertnet.org/index.html), IREKANI (http://unibio.unam.mx/irekani/) and iNaturalist (www.iNaturalist.com.mx). To ensure consistency, only records from 2000 to 2023 were included, as significant land-use changes and climatic shifts in Mexico have primarily occurred over the last two decades. For example, between 2002 and 2019, Mexico lost 594 thousand hectares of humid primary forest, placing it amongst the top nine tropical countries in terms of primary forest loss (Hansen et al. 2013). The occurrence data were processed using the EcoNicheS package for R (Marmolejo et al. 2024) following these steps: (1) previsualisation of the data to remove erroneous or geographically implausible records, (2) elimination of duplicate entries and (3) subsampling to avoid pseudoreplication, ensuring that only records at least 1 km apart were retained. This method significantly reduces model overfitting (Segurado et al. 2006; Boria et al. 2014). After filtering, 73 records for *A. altamirani* remained for analysis (Fig. 2B). Climatic variables were sourced from WorldClim version 2.1 (Fick and Hijmans 2017) at a 1 km resolution. Topographic variables, including elevation, slope and aspect, were derived from elevation data using ArcMap 10.5 (Fick and Hijmans 2017). Land-cover variables, such as soil use and vegetation (series VI, scale 1:250000), were obtained from the National Institute of Statistics and Geography (INEGI 2017). The land-cover layer, based on satellite images from 2014 and last updated in 2017, was processed by

extracting different land-cover types, converting them into raster format and resampling them from categorical to continuous variables. This was achieved through a method that averages the eight surrounding pixel values and the previous pixel value (7 × 7 mean), as described by Hirzel et al. (2001). This procedure was performed using IDRISI TerrSet 18.21 software (Clark Labs 2020) through the Filter module (Gidey et al. 2017). All layers were handled in raster format with a 1 km resolution using the raster package (Hijmans 2023) in R (R Core Team 2022). A Pearson's correlation analysis, conducted with ENMTools (Warren et al. 2010) and implemented through the shinydashboard EcoNicheS for R package (Marmolejo et al. 2024), helped to discard highly correlated variables ($r^2 > 0.7$; Dormann et al. (2013)). The selected variables deemed crucial for amphibian presence (Vargas-Jaimes et al. 2021; Ruiz-Reyes et al. 2024), included the percentages of grassland arid vegetation, *Pinus* forest, *Quercus* forest, *Abies* forest, agricultural land and cloud forest. Climatic factors, such as maximum temperature of the warmest month (BIO5), minimum temperature of the coldest month (BIO6), precipitation of the wettest month (BIO13) and precipitation of the driest month (BIO14), were also considered. The distance to urban areas was excluded to avoid bias, as these areas are more easily accessed by observers (Araujo and Guisan 2006). Instead, both current and future urban zones, derived from distribution maps, were assigned zero habitat suitability (González-Fernández et al. 2018; Sunny et al. 2019; Vargas-Jaimes et al. 2021; Rubio-Blanco et al. 2024).

Environmental niche modelling

Environmental niche modelling for *Ambystoma altamirani* was performed using the Maxent algorithm (Phillips et al. 2006) through the ENMeval 2.0 package (Kass et al. 2021) in R to determine the most suitable model settings. Multiple models were generated, testing various combinations of regularisation values and feature classes, including linear (L), quadratic (Q), product (P), threshold (T) and hinge (H). A total of 100,000 background points were randomly generated and the block approach of ENMeval was used to spatially partition occurrences, as per the methodology of Radosavljevic and Anderson (2014). This method creates four non-overlapping geographic bins to ensure spatial independence between the training and testing datasets (Fourcade et al. 2018). Model performance was assessed using the area under the curve (AUC) from receiver operating characteristic (ROC) plots (Metz 1978; Phillips et al. 2006). Partial-receiver operating characteristic curves (Partial-ROC; Peterson et al. (2008)) were generated using the EcoNicheS package. To estimate potential distribution areas, we applied both the 10th percentile training presence threshold and the 60% percentile training presence threshold, allowing for robust predictions of *A. altamirani*'s present and future distributions in response to environmental changes.

Land cover and climate change

Land-use and vegetation projections for the year 2050 were generated using the Land Change Modeller for Ecological Sustainability (LCMES) module in IDRISI TerrSet, based on land-use and vegetation layers from 2011 (series V;

INEGI 2011) and 2014 (series VI; INEGI 2017). The model employed artificial neural networks, Markov chain matrices and transition suitability maps using multilayer perceptron or logistic regression (Mas et al. 2014; Ansari and Golabi 2019; Hasan et al. 2020). This approach predicts land-cover changes between different raster images from various time periods with the same number of classes in the same order (Mas et al. 2014). The analysis evaluates quantitative change by charting gains and losses across land-cover types (Mishra et al. 2014; Hasan et al. 2020) and estimates net change, persistence and specific transitions between land-cover classes (Gibson et al. 2018; Hasan et al. 2020). Finally, the algorithm applies a Markov chain model to forecast land-cover changes from time t = 1 to time t+1, using transition probability and area matrices for each land-cover class (Hasan et al. 2020). Current and future urban areas were designated as areas of zero habitat suitability. Future potential distribution maps were generated using future bioclimatic variables from the CNRM-CM5 (CN) and MPI-ESM-LR (MP) climate models for the year 2050, under the most extreme climate scenario (RCP 8.5). These climate models were selected from WorldClim's downscaled CMIP5 data (https://worldclim.org/data/cmip5_2.5m.html) due to their proven effectiveness for Central America (Hidalgo and Alfaro 2015) and their high performance amongst the 40 available models (Kamworapan and Surussavadee 2019). The resulting continuous maps were reclassified into binary maps using both 90% and 10th percentile training presence thresholds. These thresholds exclude the lowest 10% of locality values, offering a more reliable prediction of habitat suitability (Radosavljevic and Anderson 2014). The binary maps were then used to evaluate changes in *A. altamirani*'s potential distribution under future climate scenarios. To assess the contribution of current natural protected areas (NPAs) in conserving *A. altamirani*, we calculated the percentage of highly-suitable areas that overlap with NPAs using both the 60% and 10th percentile training presence thresholds. This analysis was conducted using the EcoNicheS for R package. Finally, a comprehensive search was conducted using Global Forest Watch to assess the areas where the greatest loss of potential distribution for Ambystoma altamirani was identified. The objective was to determine whether these reductions in distribution are directly linked to the loss of vegetation cover. The analysis focused on correlating the predicted habitat loss from ecological niche models with observed deforestation trends, providing insight into the extent to which habitat degradation is contributing to the species' declining range.

Results

Ecological niche modelling

Based on the results of the ENMeval analysis, the L model with a regularisation multiplier (RM) of 1 was identified as the best-performing model for predicting the current distribution of *A. altamirani* in 2014, as well as its future distribution under the CN85 climate scenario in 2050. For the MP85 scenario in 2050, however, the optimal model was found to be the L model with a RM of 2 (Table 1). After applying filtering criteria to the occurrence data, a total of 73 records were retained for model calibration (Fig. 1). ENMeval models were used to estimate both current and future distributions under two global climate models (GCMs),

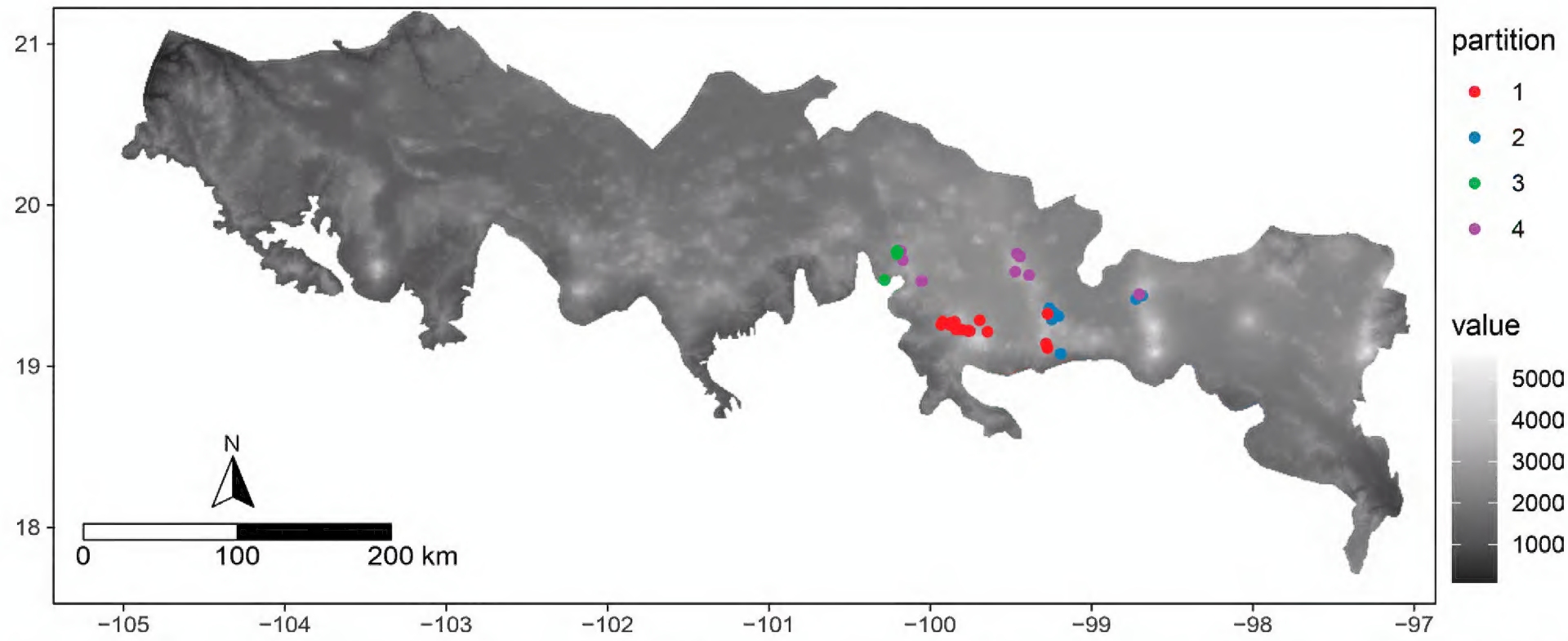

Figure 1. Occurrence records with the block method partition, including the *Ambystoma altamirani* accessible area (M) represented by grey-scale elevation layer.

Table 1. Predictive performance of present and future ENMeval distribution models for *Ambystoma altamirani* with two different global climate models and land-cover changes.

Year	RM	FC	10 percentile training presence	ROC	Partial-ROC
2014	1	L	0.3	0.98	1.968 ($p < 0.001$)
2050 cn85	1	L	0.3	0.98	1.968 ($p < 0.001$)
2050 mp85	2	L	0.3	0.98	1.968 ($p < 0.001$)

CN85 and MP85 and the models showed significantly better predictive performance than random chance (Table 1). The area under the curve (AUC) for all models was consistently high, with a value of 0.98, indicating strong predictive power ($p < 0.001$). This was supported by partial ROC bootstrap tests, which revealed significant empirical AUC ratios of 1.968 across all models ($p < 0.001$; Table 1), further confirming the robustness of these predictions (Table 1). The environmental variables that contributed the most to the species' distribution were the minimum temperature of the coldest month (Bio6), with a high permutation importance of 51.8%, followed by *Abies* forest cover, which accounted for 20.3% of the variation in habitat suitability. Other significant factors included slope (6.8%), altitude (6%) and arid vegetation cover (5.6%) (Fig. 2, Table 2). The positive correlation of Bio6 and *Abies* forest with the species' presence suggests that *A. altamirani* thrives in colder environments and forested areas, particularly in higher altitudes with dense *Abies* coverage (Fig. 2). Conversely, the presence of arid vegetation and *Quercus* forest negatively impacted the habitat suitability, highlighting the species' preference for moist, forested environments (Fig. 2, Table 2). In terms of future distribution under climate change scenarios, the models predicted a contraction in suitable habitat for *A. altamirani* by 2050. Using a 60% threshold, the models projected a habitat loss of 6.02% under the MP85 scenario and a larger loss of 13.95% under the CN85 scenario (Fig. 3, Table 3). This decline suggests that *A. altamirani* will face increasing challenges in maintaining its current range as climate conditions shift, particularly in the more sensitive areas of its distribution. When considering the 10 percentile training presence threshold, which accounts for potential future range loss,

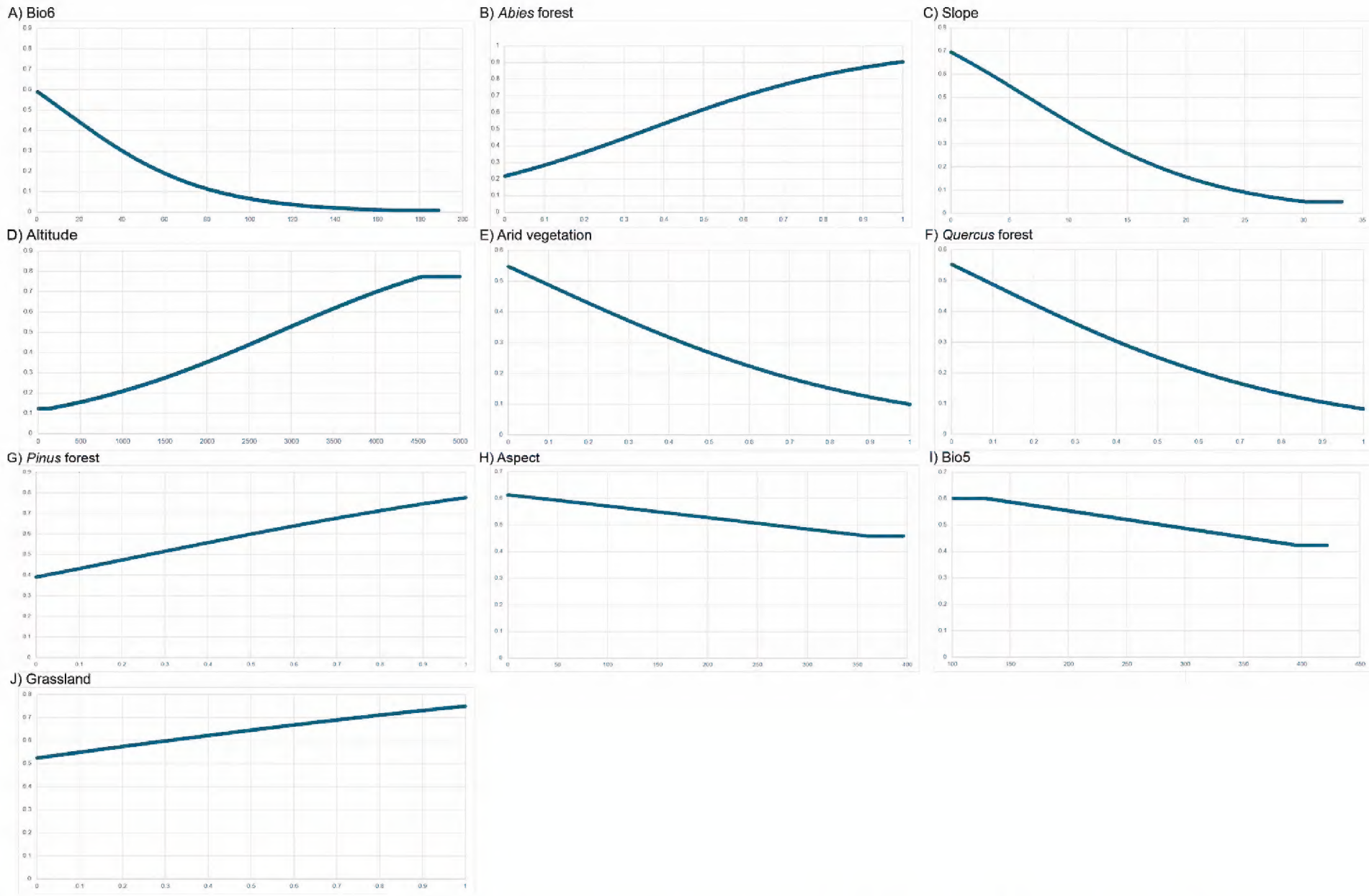

Figure 2. Response curves of the variables that influence the potential distribution of *Ambystoma altamirani*.

Table 2. The most important environmental variables associated with the presence of *Ambystoma altamirani*.

Variable	Permutation importance	Correlation
Bio6	51.8	Positive
Abies forest	20.3	Positive
Slope	6.8	Negative
Altitude	6	Positive
Arid vegetation	5.6	Negative
Quercus forest	4.5	Negative
Pinus forest	1.9	Positive
Aspect	1.6	Negative
Bio5	0.8	Negative
Grassland	0.7	Positive

the projected reductions were slightly lower, with losses between 4.73% (MP85 scenario) and 9.61% (CN85 scenario) (Fig. 3, Table 3). These habitat losses were most pronounced in critical areas such as the Sierra de las Cruces forest (Fig. 4), specifically within the south of the Sierra de las Cruces and Chichinautzin Biological Corridor (Fig. 4). These regions are known biodiversity hotspots and serve as key habitats for *A. altamirani*. The predicted contraction in these areas highlights the potential vulnerability of this species to habitat fragmentation and climate-induced shifts in environmental conditions (Fig. 4, Table 3).

Overall, these findings suggest that *A. altamirani* is highly dependent on specific environmental conditions, particularly cold temperatures and forested

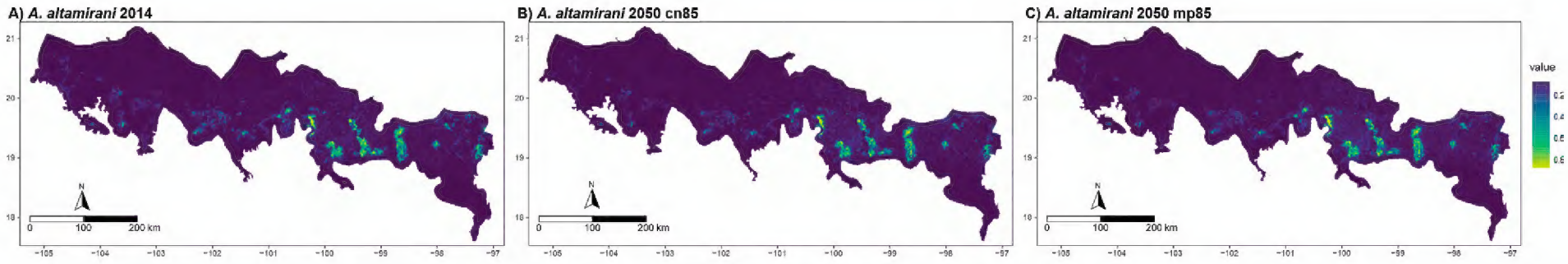

Figure 3. Present (2014) and future (2050) potential distribution maps for *Ambystoma altamirani*, generated for 2014 and under future climate scenarios CN85 and MP85 for 2050.

Table 3. Present and future suitability area (km²) and percentage of area loss of *Ambystoma altamirani* with two different global climate models and land-cover changes.

60%					10 percentile training presence				
2014 (km²)	**2050 cn85 (km²)**	**Loss 2014–2050 (%)**	**2050 mp85 (km²)**	**Loss 2014–2050 (%)**	**2014 (km²)**	**2050 cn85 (km²)**	**Loss 2014–2050 (%)**	**2050 mp85 (km²)**	**Loss 2014–2050 (%)**
1273.94	1096.22	**13.95**	1197.19	**6.02**	3410.1	3082.34	**9.61**	3248.65	**4.73**

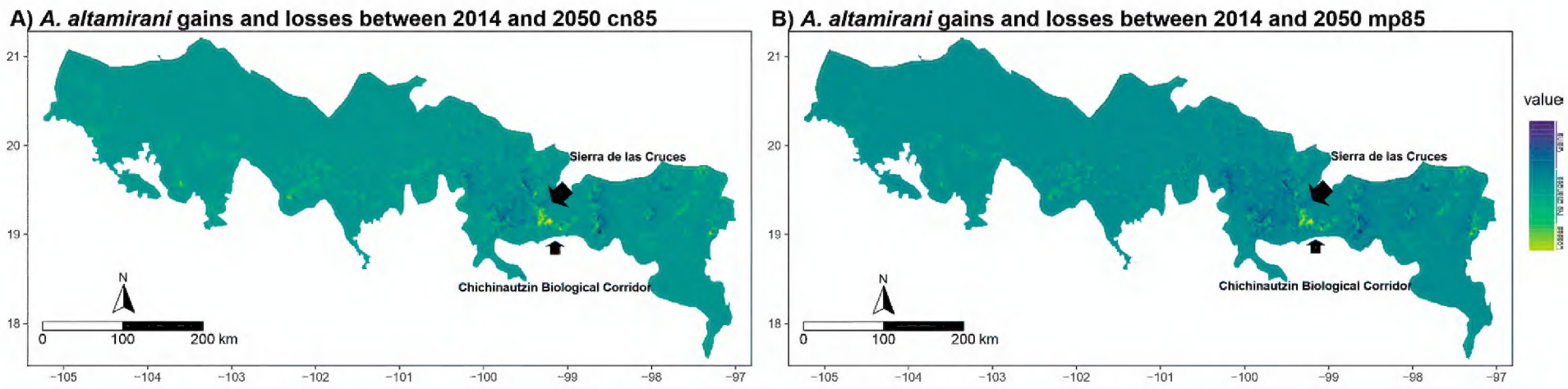

Figure 4. Gains and losses in the potential distribution of *Ambystoma altamirani* under two different global climate models (CN85 and MP85) and in response to land-use and vegetation cover changes.

habitats, which are projected to be significantly reduced in the coming decades. The models also underscore the importance of protecting key habitats, especially in the Sierra de las Cruces Forest, where the species faces the greatest risk of habitat loss. Conservation strategies should focus on mitigating the effects of climate change and preserving forested areas to ensure the survival of *A. altamirani* in the future.

A map was generated depicting the potential distribution of *A. altamirani* within areas where its occurrence is known (Fig. 5), as well as the species' potential distribution within federal and state-level protected natural areas (Fig. 6, Table 4). The results indicate that the regions with the highest potential distribution for *A. altamirani* include the Sierra de las Cruces, the Chichinautzin Biological Corridor (Fig. 6D) and the Izta-Popo Zoquiapan. However, current population records of *A. altamirani leorae* are limited to the Monte Tlaloc area (Fig. 6E. F), despite the broader potential distribution identified in the the Izta-Popo Zoquiapan area (Fig. 6E), the Nevado de Toluca Volcano (Fig. 6E) and the Sierra Chincua (Fig. 6D). These areas represent key conservation zones where suitable habitat conditions are present for the species, highlighting their importance in the conservation strategy for *A. altamirani* (Fig. 6).

The results indicate that, by 2050, both global climate models (CN85 and MP85) project a reduction in suitable habitat for *A. altamirani* within protected natural areas, using a 60% threshold. Under the CN85 scenario, the species is expected to

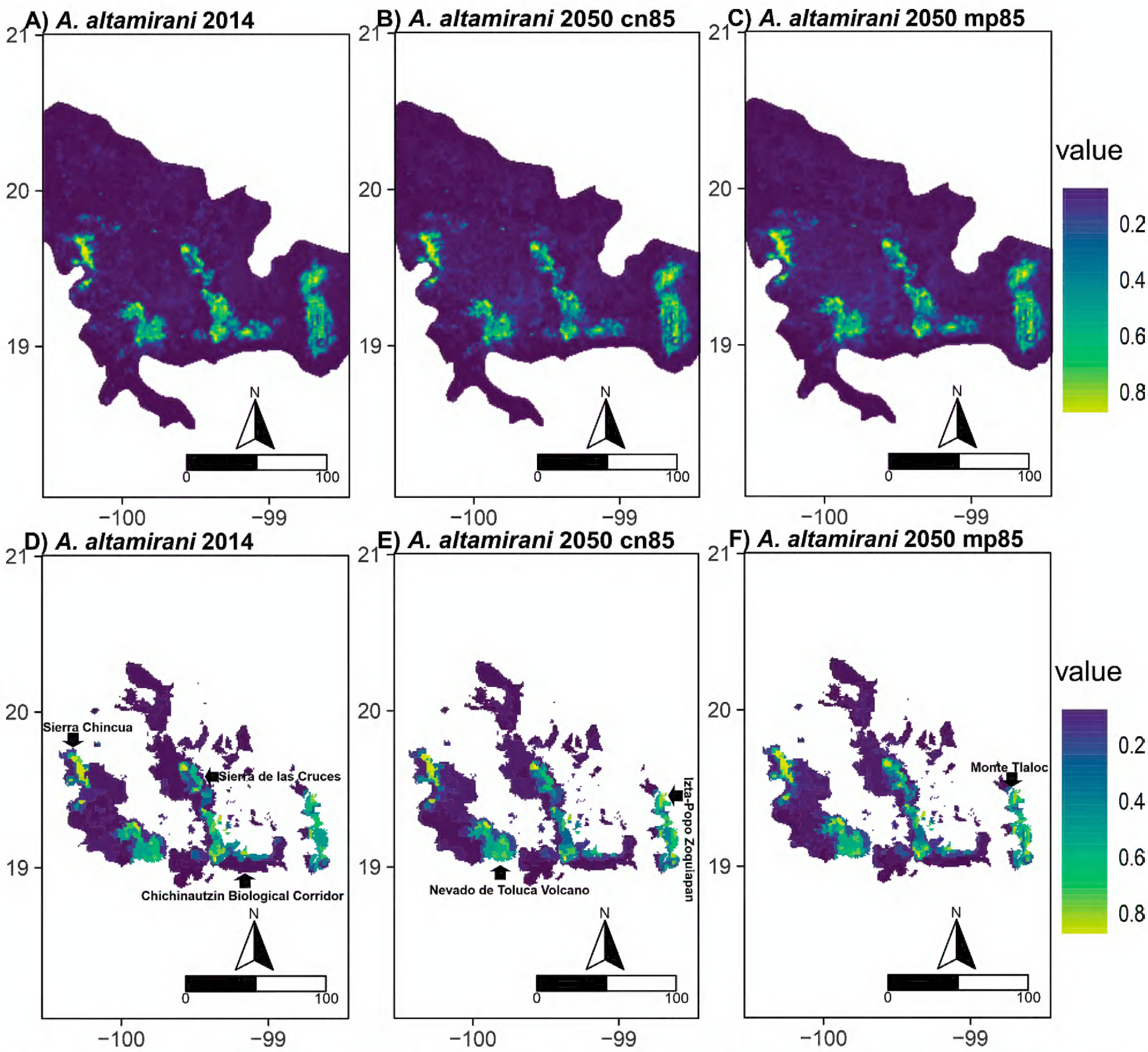

Figure 5. Present (2014) and future (2050) potential distribution maps for *Ambystoma altamirani*, considering known areas of occurrence and locations within protected natural areas, generated for the 2014 baseline and future climate scenarios CN85 and MP85 for 2050.

experience a significant 12.93% habitat loss, whereas the MP85 model predicts a more moderate reduction of 5.12%. Additionally, using the 10 percentile training presence threshold, the CN85 model shows an 8.11% decrease in suitable habitat, with a smaller reduction of 1.91% under the MP85 scenario. These findings emphasise the considerable impact of climate change on the future availability of suitable habitats for this critically endangered species (Table 4).

The results show varying levels of forest cover loss across four municipalities (Tlalpan, Álvaro Obregón, Jalatlaco and Ocuilan) between 2001 and 2023. Tlalpan experienced the most dramatic increase in forest loss in 2023, reaching 99.29 km^2, with a smaller peak in 2022 (21.62 km^2). In Álvaro Obregón, the highest deforestation occurred in 2018 (11.05 km^2), followed by 2019 (9.82 km^2). Jalatlaco had its most significant losses in 2018 (50.97 km^2) and 2017 (21.26 km^2). Ocuilan showed similarly high levels of deforestation in 2018 (63.75 km^2) and 2017 (30.24 km^2), with another spike in 2022 (28.56 km^2).

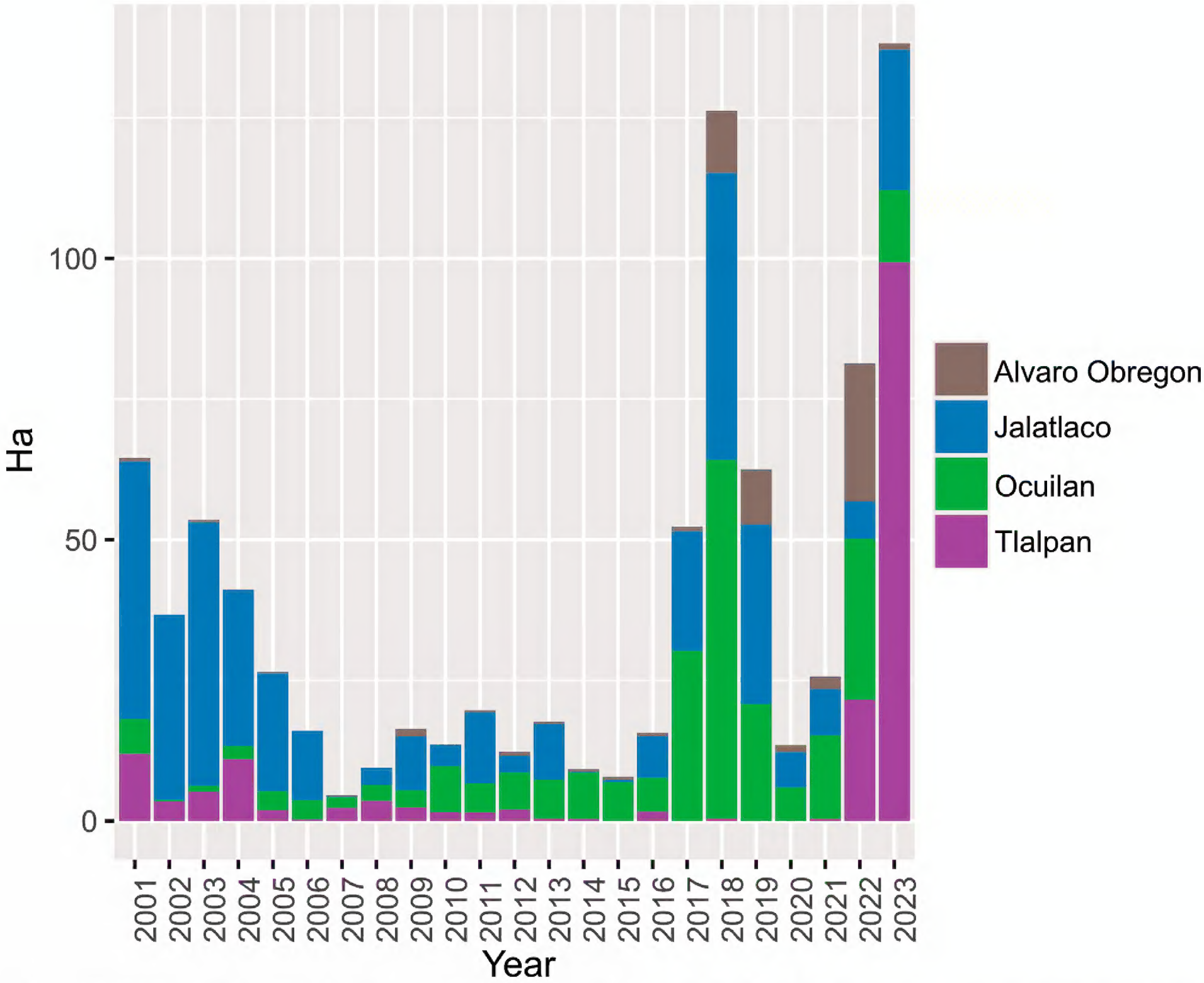

Figure 6. Percentage of forest cover lost between 2001 and 2023 within the Sierra de las Cruces and the Chichinautzin Biological Corridor, as determined using data from Global Forest Watch, considering the municipalities in the region.

Table 4. Present and future suitability area (km²) and percentage of area loss of *Ambystoma altamirani* with two different global climate models and land-cover changes in the ANPS.

60%					10 percentile training presence				
2014 (km²)	**2050 cn85 (km²)**	**Loss 2014–2050 (%)**	**2050 mp85 (km²)**	**Loss 2014–2050 (%)**	**2014 (km²)**	**2050 cn85 (km²)**	**Loss 2014–2050 (%)**	**2050 mp85 (km²)**	**Loss 2014–2050 (%)**
930.88	810.50	**12.93**	883.25	**5.12**	2123.67	1951.48	**8.11**	2083.09	**1.91**

Discussion

The findings of this study underscore the significant threats faced by *Ambystoma altamirani*, a critically endangered amphibian, whose survival depends on highly specific environmental conditions found in the TMVB (Ruiz-Reyes et al. 2024; Sunny et al. 2024). Habitat degradation, land-use changes, invasive species and climate change are all converging to increase the vulnerability of this microendemic species, reinforcing the need for urgent and targeted conservation actions. The results of the ecological niche models (ENMs) indicate that *Ambystoma altamirani* relies heavily on temperate forests dominated by *Abies* and *Pinus* species (Reyes-Olivares et al. 2024; Ruiz-Reyes et al. 2024; Sunny et

al. 2024), with the minimum temperature of the coldest month (Bio6) being the most important variable contributing to its distribution (51.8%). The fragmentation and degradation of these habitats, particularly in the Sierra de las Cruces region, are of particular concern (López-García and Navarro-Cerrillo 2021; Ruiz-Reyes et al. 2024). Both legal and illegal logging, along with agricultural expansion and urbanization, continue to erode the integrity of these forested areas, as confirmed by multiple studies (García 2011; López-García and Navarro-Cerrillo 2021; González-Fernández et al. 2022; Segarra et al. 2024).

It is also important to consider that these distribution models are predicting potential suitable areas for the species. However, even though some regions may appear to have the necessary environmental conditions, *A. altamirani* is not present in many of them. This suggests that the potential distributions predicted by the models might be overestimated. Consequently, *A. altamirani* could be facing even greater conservation pressures than what these models suggest, given that its actual range might be more restricted than the potential range indicates. This highlights the need for targeted conservation actions that focus on both habitat protection and understanding the species' real-world limitations within its predicted range. The loss of critical forest cover between 2011 and 2014 and continued deforestation since then have compounded the risk of extinction for *A. altamirani*, as these forests provide essential microhabitats that are becoming increasingly scarce (López-García and Navarro-Cerrillo 2021; González-Fernández et al. 2022). In particular, the high correlation between *Abies* forest cover and *A. altamirani's* presence suggests that conservation efforts should prioritize mixed *Abies* forest along with aquatic habitats as streams (Ruiz-Reyes et al. 2024). Areas dominated exclusively by *Pinus* forests were found to be less suitable, underscoring the importance of maintaining diverse forest ecosystems to support viable populations (Jõks et al. 2023; Ruiz-Reyes et al. 2024). The trend of forest loss, particularly in the TMVB, jeopardises the future of this amphibian and highlights the urgent need for stricter enforcement of land-use regulations and sustainable forest management (García 2011; López-García and Navarro-Cerrillo 2021; Vargas-Jaimes et al. 2021; González-Fernández et al. 2022).While *A. altamirani* may have some capacity to adapt to changing environmental conditions (Sánchez- Sánchez et al. 2024). climate change poses a significant long-term challenge for the species. Our models predict a notable reduction in suitable habitat under future climate scenarios, with potential losses reaching up to 13.95% by 2050 (CN85 scenario). This habitat contraction will primarily affect areas that are already under pressure from human activities, such as the southern part of the Sierra de las Cruces and the Chichinautzin Biological Corridor (López-García and Navarro-Cerrillo 2021; Vargas-Jaimes et al. 2021). The observed patterns of forest cover loss in Tlalpan, Álvaro Obregón, Jalatlaco and Ocuilan between 2001 and 2023 are particularly concerning for *A. altamirani*, as our ecological niche models (ENMs) predicted significant reductions in the species' potential distribution in these areas. The most substantial deforestation events in 2018 and 2023 coincide with the predicted loss of suitable habitat, further exacerbating the conservation challenges for this critically endangered species. In particular, the deforestation in Tlalpan and Ocuilan, which reached 99.29 km^2 and 63.75 km^2, respectively, in recent years, threatens critical forest habitats that *A. altamirani* relies on, especially

in regions where *Abies* and *Pinus* forests are essential for its survival. The increased land-use changes in these areas, coupled with climate change, are likely to fragment the already limited habitats further, isolating populations and increasing the risk of local extinctions.

These findings highlight the urgent need for targeted conservation actions to mitigate habitat loss and protect the remaining suitable environments for *A. altamirani*, especially in areas identified as high-risk through both deforestation trends and species distribution models. Likewise, these areas are known biodiversity hotspots and are critical for maintaining ecological connectivity, which is vital for the species' survival (Kirk et al. 2023; Qian et al. 2023; Zhou et al. 2023). The predicted loss of suitable habitat is particularly concerning given *A. altamirani's* limited dispersal abilities (Ruiz-Reyes et al. 2024). The species is highly dependent on cold, oxygen-rich rivers and climate change is expected to reduce the availability of such aquatic habitats, further fragmenting populations. Despite the potential resilience of *A. altamirani* to rising aquatic temperatures observed under experimental conditions (Sánchez-Sánchez et al. 2024), as temperatures rise and precipitation patterns shift, the availability of cold-water streams could decline, leaving the species isolated in smaller, fragmented patches of suitable habitat (Johnson et al. 2024; Lamouille-Hébert et al. 2024). This isolation could hinder genetic exchange between populations, increasing the risk of local extinctions (Sunny et al. 2022). Mitigating the impacts of climate change will require a multifaceted approach that includes habitat restoration, the creation of ecological corridors to facilitate movement between suitable habitats (Sunny et al. 2022) and the protection of areas that are expected to remain suitable under future climate scenarios like the northern part of the Sierra de las Cruces, the Nevado the Toluca Volcano and the Sierra Chincua. The use of future bioclimatic variables in our models provided valuable insights into how the distribution of *A. altamirani* may shift, allowing conservationists to prioritize areas that will remain critical for the species' survival in the coming decades. In addition to habitat degradation and climate change, *A. altamirani* faces significant threats from invasive species, particularly *Oncorhynchus mykiss* (Estrella-Zamora et al. 2018; Zamora et al. 2018; Guerrero-de La Paz et al. 2020; Sunny et al. 2024). The expansion of trout farming, especially in the Sierra de las Cruces region, has further degraded critical habitats (Zambrano et al. 2010; Estrella-Zamora et al. 2018; Guerrero-de La Paz et al. 2020; Sunny et al. 2024). Furthermore, it is essential to investigate how *O. mykiss* may affect *A. altamirani* populations in other areas where the species is present. Additionally, the establishment of trout farms, particularly in municipalities like Isidro Fabela, has led to the degradation of riverine habitats, reducing the availability of suitable breeding sites for *A. altamirani*. Moreover, agricultural expansion in the TMVB exacerbates the pollution of aquatic ecosystems (Häder et al. 2020; Mushtaq et al. 2020). The widespread use of agrochemicals contaminates the rivers and streams where *A. altamirani* resides, further reducing habitat quality and increasing the species' susceptibility to diseases and environmental stressors (Suárez et al. 2021; Zambrano-Fernández et al. 2022; Paetow et al. 2023). Sustainable agricultural practices and stricter regulations on agrochemical use are essential to improving water quality and reducing the pressures on amphibian populations (Suárez et al. 2021; Zambrano-Fernández et al. 2022; Paetow et al. 2023).

Conservation implications

Given the complex combination of threats facing *A. altamirani*, conservation strategies must adopt an integrated approach that addresses habitat loss, invasive species management and climate resilience. Protecting and restoring temperate forests, particularly those with a high proportion of *Abies* cover, is critical for maintaining viable populations (Sunny et al. 2018; González-Fernández et al. 2019). Special attention should be given to the Sierra de las Cruces and surrounding areas, which are home to the most vulnerable populations of *A. altamirani*. In addition, the regulation of trout farming and the removal of invasive *O. mykiss* from key habitats could alleviate some of the pressures on native amphibian populations. This, combined with habitat restoration and the implementation of ecological corridors, could help mitigate the effects of habitat fragmentation. Finally, addressing climate change through landscape-level conservation planning is essential for the long-term survival of *A. altamirani*. Identifying areas that are likely to remain suitable under future climate conditions and ensuring that these areas are adequately protected within natural protected areas (NPAs) will be critical for building climate resilience into conservation strategies. The overlap between suitable habitats and NPAs, as evaluated in this study, provides a roadmap for prioritizing areas for conservation and restoration efforts. Restoring degraded ecosystems are essential to mitigate the negative impacts on *A. altamirani*. Given the species' narrow habitat range and limited dispersal abilities, maintaining habitat connectivity and protecting the species' remaining habitats are critical for preventing its extinction.

Conclusion

Ambystoma altamirani is at a critical juncture, facing a confluence of threats from habitat loss, invasive species, pollution and climate change. Immediate action is required to protect its remaining habitats and ensure the long-term survival of the species. Conservation efforts must focus on habitat protection, sustainable land-use practices, invasive species management and climate adaptation strategies. By taking a holistic approach, we can help safeguard this unique species and the valuable ecosystem services it provides for future generations.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

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Author contributions

All authors contributed to the study conception and design, material preparation, data collection and analysis. The first draft of the manuscript was written by Armando Sunny and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

All of the data that support the findings of this study are available in the main text.

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